LIQUID PROPELLANT BLAST YIELDS FOR
DELTA IV HEAVY VEHICLES

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ABSTRACT

Launch vehicle propulsion systems contain liquid propellants that may mix and explode when impacting the ground intact following launch attempts failing early in flight. Launch area risk analysis tools characterize the air shock potential of promptly reacting liquid propellants in these events using models of the blast yield as a function of propellant material, weight, impact velocity, and impact surface hardness. Air blast yields from these events are typically described in terms of the ratio of the equivalent weight of TNT to the total weight of the propellant involved, based on the air shock overpressure generated. The Delta IV Heavy is unique among currently operating heavy space lift vehicles in both size and configuration, with three Common Booster Cores (CBCs), each containing some 450,000 lb of liquid propellants. The blast yield model for all three CBCs exploding simultaneously during an intact impact may be excessively conservative. Recent hydrocode simulations show significant time delays between the development of fuel and oxidizer mixing interfaces in adjacent CBC bulkheads. Early mixing of propellants in a CBC may lead to the dispersal of propellants in adjacent CBCs that would otherwise mix and react promptly. This suggests that only one or two CBCs are likely to contribute significantly to the overall blast yield. Further confirmation of this finding may be possible with higher fidelity simulations.

INTRODUCTION

Launch vehicle propulsion systems contain large quantities of energetic materials that may explode when impacting the ground following failed launch attempts. Software tools commonly used to compute blast risks for such events to people on the ground characterize the air shock potential of the promptly reacting propellants using models of the blast yield as a function of the propellant material type, weight, impact velocity, and impact surface hardness [1]. Blast yields in these models are often described in terms of the ratio of the equivalent weight of TNT to the total weight of the propellant involved, based on the air shock overpressure generated in the explosions. Liquid propellant blast yield models currently in use predict generally increasing yields with increasing impact speeds.

Liquid propellant yield models currently used by ACTA for launch risk analyses are derived primarily from data acquired in the Project PYRO test series, performed in the 1960's [2]. The curves have a high degree of safety built into them, being roughly fit to PYRO data using substantially conservative assumptions, as detailed in previous ACTA reports [3][4]. For a particular vehicle evaluated, these yield-velocity relationships are used along with multiple simulations of the vehicle failure on or near the pad to predict various explosive yields and associated probabilities of occurrence. The yields may be sorted into bins to form yield histograms.

Examples of yield histograms are shown in Figure 1 for a Delta IV Heavy vehicle launched from the Western Launch Range at Vandenberg AFB. The yield histograms were developed by simulating multiple instances of the vehicle failure in malfunction turn and engine loss-of-thrust failure modes in a Monte Carlo process, and determining in each simulation if the fallback time is long enough for the Mission Flight Control Officer (MFCO) to destroy the vehicle before it impacts the ground intact [5]. If the vehicle does not impact intact due to a destruct action taken by the MFCO, then the blast yield is treated as minimal [6] and a yield of zero is recorded for the simulation. If, on the other hand, the vehicle does impact intact, then PYRO yield curves for the particular propellant combination are used along with the impact velocity to predict the blast yield in the simulation. In either case the relative probability of the particular yield recorded and the probability of the particular failure mode occurring are used to compute

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14. ABSTRACT
Launch vehicle propulsion systems contain liquid propellants that may mix and explode when impacting the ground intact following launch attempts failing early in flight. Launch area risk analysis tools characterize the air shock potential of promptly reacting liquid propellants in these events using models of the blast yield as a function of propellant material, weight, impact velocity, and impact surface hardness. Air blast yields from these events are typically described in terms of the ratio of the equivalent weight of TNT to the total weight of the propellant involved, based on the air shock overpressure generated. The Delta IV Heavy is unique among currently operating heavy space lift vehicles in both size and configuration, with three Common Booster Cores (CBCs), each containing some 450,000 lb of liquid propellants. The blast yield model for all three CBCs exploding simultaneously during an intact impact may be excessively conservative. Recent hydrocode simulations show significant time delays between the development of fuel and oxidizer mixing interfaces in adjacent CBC bulkheads. Early mixing of propellants in a CBC may lead to the dispersal of propellants in adjacent CBCs that would otherwise mix and react promptly. This suggests that only one or two CBCs are likely to contribute significantly to the overall blast yield. Further confirmation of this finding may be possible with higher fidelity simulations.

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the absolute probability of the particular yield occurring, which is then added to the running probability total in the bin for the particular yield. In this way, the yield histogram is developed after numerous simulations.
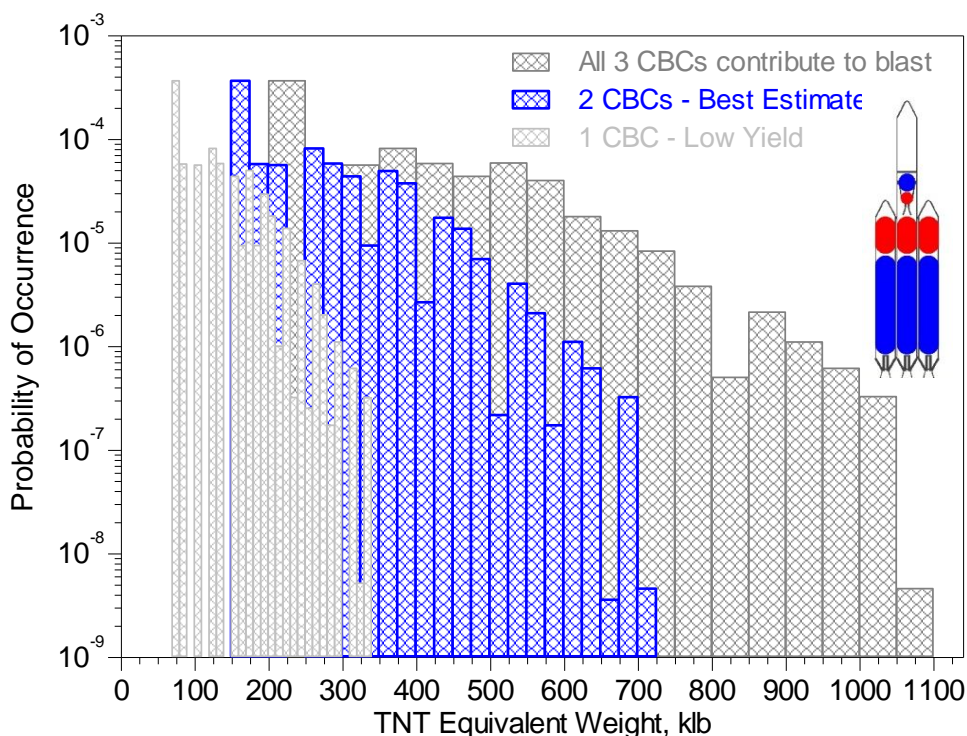

Figure 1. Delta IV Heavy Combined Yield Histograms for Western Range Launches

The Delta IV Heavy is unique among currently operating heavy space lift vehicles in both size and configuration, as it has three large Common Booster Cores (CBCs), each containing some 450,000 lb of liquid propellants. If the vehicle impacts the ground intact and all three of its CBCs explode simultaneously, up to 1.4 million lb of liquid oxygen and liquid hydrogen (LO_2/LH_2) may be involved and at least partially contribute to the blast yield. The maximum credible yield may be over one million lb TNT for Western Range launches. This condition is represented by the largest of the three yield histograms (with the largest yield bins) shown in Figure 1.

If, on the other hand, one of the CBCs explodes significantly earlier than the other two (on a millisecond timescale) then the rapidly expanding blast wave and initial combustion products may potentially drive apart the unmixed reactants in the other CBCs, delaying their mixing and reaction until the blast wave generated initially in the event has departed. The remaining propellants may mix and react at a later time in the event, and so contribute to the slower developing fireball, but their energy release would occur too late in the event to contribute significantly to the overall blast yield. This situation is represented by the smallest yield histogram shown in Figure 1. The intermediate histogram in this figure represents the case where two of the three CBCs react quickly and disperse the reactants in the third so as to prevent them from contributing to the blast yield.

Since the PYRO LO_2/LH_2 yield model was originally developed using data from sled and tower-drop impact tests with coaxially aligned liquid propellant tank configurations, the question may be raised as to whether the entire quantity of propellants from all three non-coaxially aligned CBCs should be treated as participating in the explosion in such a way as to potentially contribute to the blast yield (with the entire weight of all three CBC propellant applied to the PYRO yield curve) *or* whether only one or two of the CBCs plus some small fraction of the remaining CBC(s) should be applied to the PYRO model. If

the tanks rupture in the bulkhead chambers such that mixing interfaces between the LO_2 and LH_2 tanks for all three CBCs occur simultaneously, then a reasonable argument can be made for all three CBCs participating in the blast yield-producing explosion. The ignition of propellants in all three CBCs would then occur at nearly the same time, leading to the participation of all three in the generation of a blast wave.

If, on the other hand, the time between CBC mixing interfaces is on the order of several milliseconds or greater, then the rapidly expanding combustion products may interfere with the mixing of propellants in the remaining CBC(s), thereby reducing or eliminating the potential of the remaining CBC(s) to contribute to the blast yield. The propellant from all three CBCs would still be expected to participate in the relatively slow development of a large fireball, but not necessarily contribute to the strength of the faster moving blast wave. In such a case, it would be more appropriate to apply the propellant weight of only the first-igniting CBC to the PYRO model, plus some fraction of the propellants from the remaining two CBCs to account for incidental contact of the fuel and oxidizer in these CBCs, as the combustion products and unreacted propellants continue to expand in the explosion.

VEHICLE IMPACT SIMULATIONS

To assess the potential of propellants from two or more CBCs to participate in the blast yield, the shock physics code CTH [7] was used estimate the relative timing of the development of the mixing interfaces between the propellants in the CBC bulkhead chambers. The LO_2 and LH_2 equation-of-state (EOS) models are taken from the CTH SESAME database for these materials [8]. The physical model used is a simplification of an actual vehicle, but is intended to capture the key characteristics affecting the location of the major portion of the propellant mixing upon impacting the ground. The tank wall thicknesses and material (0.8 cm thick 2024-T4 aluminum, CTH Mie-Grüneisen EOS [8]) were selected to provide a large factor of safety in order to reduce or eliminate the possibility of premature failure of any part of the tank walls. The ground medium chosen as an impact surface has an EOS model consisting of CTH SESAME tabular data for granite.

PREVIOUS ANALYSES

Similar simulations were performed in 2007 for Delta IV Medium vehicles to assess the ability of the vehicle to penetrate soft impact surfaces before breaking up, and thus the applicability of the PYRO yield model for soft surface impacts of large liquid propellant vehicles [1]. Results of a sample simulation of a Delta IV Medium vehicle impacting into dry sand at 800 fps are shown in Figure 2. The LO_2 in this figure is shown in red and the LH_2 is shown in blue. This color convention is also used for the figures that follow showing the Delta IV Heavy vehicle impact simulations.

The first stage tanks are observed in Figure 2 to rupture in such a manner as to cause mixing at the interface of the first stage fuel and oxidizer tanks. Upon contacting the sand surface, shock waves propagate through the liquid propellants and structural elements, causing tank wall breaching beginning with the lowest (first stage oxidizer) tank. The visible rupturing of the upper stage tanks prior to significant mixing of the lower stage components suggest that the earliest tank failures occur due to shock pressures within the liquids and structure, rather than quasi-static propellant bulk pressurization causing general expansion or macro-deformation of the tank walls.
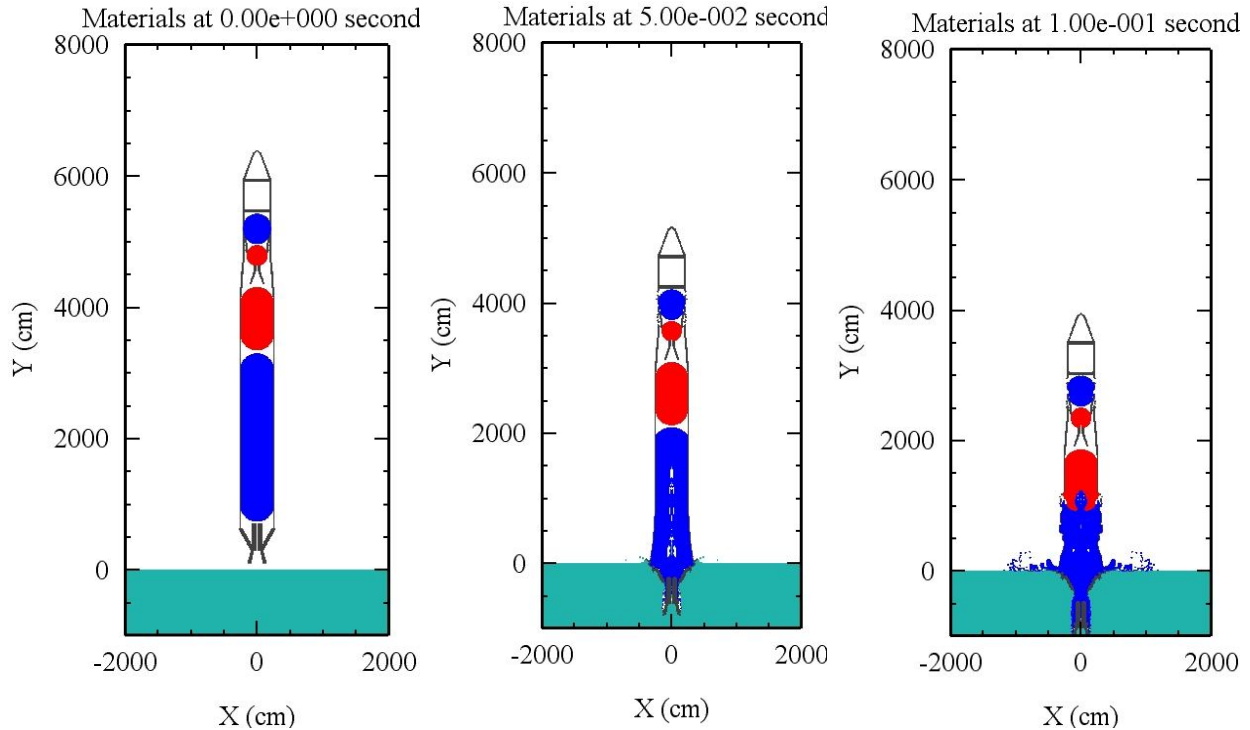
Figure 2. Delta IV Medium Upright Vertical Fallback at 800 fps into Dry Sand

Once a mixing interface appears between the propellant components in the CBC bulkhead, it is believed that prompt ignition and reactions will occur in this vicinity. Evidence supporting the prediction of prompt ignition in this type of condition was found in the PYRO sled tests, in which very prompt ignition was routinely observed for all propellants and impact surfaces evaluated [2]. LO_2/LH_2 high tower drop tests performed in the 1990's in the Hydrogen-Oxygen Vertical Impact (HOVI) test program at the White Sands Test Facility [9] also had short ignition delays, although the delays were generally longer than those in the PYRO sled tests due to the lower impact velocities used. The promptness of the ignitions in these tests was believed by the experimenters to be related to the high speed ejection of vaporized propellants in the presence of localized heat or sparks generated from the rupturing and rubbing metal and/or dialectic foam insulation surfaces.

The conclusion of the 2007 study, as exemplified in Figure 2, is that significant mixing does not occur in any impact crater in such a manner as to confine the mixing components, thereby enhancing the explosive effects. Ignition of the components tends to occur near the interface between the tanks and promptly upon contact, such that the center of the explosion is above and outside of any crater that may form in the ground following impact. This is due to failure of the liquid propellant tank domes early in the process as a result of the shock wave traveling to the tank interfaces at rates much greater than the speed of the vehicle relative to the ground.

MODEL SIMPLIFICATIONS

The main goals in each vehicle impact simulation in the present study are to identify the appearance of the propellant mixing interface in the first CBC bulkhead in which this first occurs, and to estimate the time delay between the appearances of the mixing interfaces, in order assess the potential for more than one CBC to contribute significantly to the total blast yield. CTH does not currently possess mature models for accurately simulating the ignition of rapidly combined liquid propellant components [7], however, the treatment of the liquids as inert is considered to be adequate for this purpose, since it is the

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behavior of the materials prior to ignition, rather than during or following the ignition, that is of primary interest here.

The Delta IV Heavy vehicle physical model used in the present study is a simplification of an actual vehicle, but is intended to capture the key characteristics affecting the location of the major portion of the propellant mixing upon impacting the ground. Calculations were performed in a two-dimensional rectangular coordinate system instead of in three-dimensional coordinates to make the best use of computational resources available at the time of the analysis. The effect of this simplification is believed to be conservative in that it places more the propellant materials in close proximity to that in the adjacent CBCs than if the vehicle were modeled in three dimensions.

In addition to the use of two-dimensional rectangular coordinates, some of the internal structural members and isogrid reinforcements in the exterior skin and tank walls of the physical vehicle [10] are also not included in the model. To compensate for this simplification, structural materials surrounding the enclosed propellants are thickened, thus minimizing the possibility of premature failure of the tank walls due to a lack of structural support. This change also allows for adequate resolution of the mesh using the limited computational resources available during the task. This modeling approximation may have some effect on the time delay between the appearances of mixing interfaces in adjacent CBCs, but does not seem likely to affect the qualitative conclusions as to their simultaneity or sequential order of occurrence.

The present analysis also limits the number of impact orientations, impact velocities and impact surface materials evaluated to a subset of the conditions possible for a failed Delta IV Heavy vehicle. Although an effort is made to assess a range of impact orientations, the impact velocity and material surface hardness are held constant, and the certainty of any conclusions drawn from this study should reflect these present limitations. Further studies with a wider and more finely resolved range of conditions may provide a basis for greater confidence in the conclusions drawn from such a study.

In summary, the primary modeling simplifications used in the analysis are:

- A two-dimensional rectangular coordinate system.

- Elimination of the vehicle internal structural supports and isogrid exterior reinforcements, with a compensatory increase in the wall thicknesses.

- The use of only a few impact orientation/velocity/surface combinations to represent a wide range of possible impact conditions.

IMPACT SIMULATION RESULTS

Simulation results for Delta IV Heavy vehicle impacting vertically in the upright position at 800 fps onto a granite surface are shown in Figure 3. The images in this figure show a mixing interface (with fuel and oxidizer in contact) appearing in the bulkhead between the propellant components in the middle CBC at approximately 36 ms into the simulation. The adjacent left and right CBCs do not exhibit such an interface at 36 ms, but appear to do so at approximately 48 ms or later. The estimated time difference between the appearance of the first and second mixing interfaces is then estimated to be at least 12 ms. As discussed above, once a mixing interface appears between the propellant components in the bulkhead of a CBC, there is evidence to support the claim that prompt ignition and reactions will occur in the vicinity. Although the liquid propellants are modeled as inert in this simulation, it is nevertheless reasonable to suppose that the propellants in the middle CBC bulkhead will begin to react at least 12 ms prior to those in the adjacent CBCs.

An estimate of the initial fireball expansion rate of approximately 1000 to 1500 mps was obtained from examination of video data from two HOVI tower drop tests [9]. Based on this estimate, the combustion products from the first igniting CBC would expand into the bulkhead regions of the two outer (unignited) CBCs in less than 5 ms, and thus interfere with and inhibit the mixing of the propellants from

the two outer CBCs. This would tend to greatly reduce the potential of the propellants from the outer CBCs to contribute to the total blast yield.
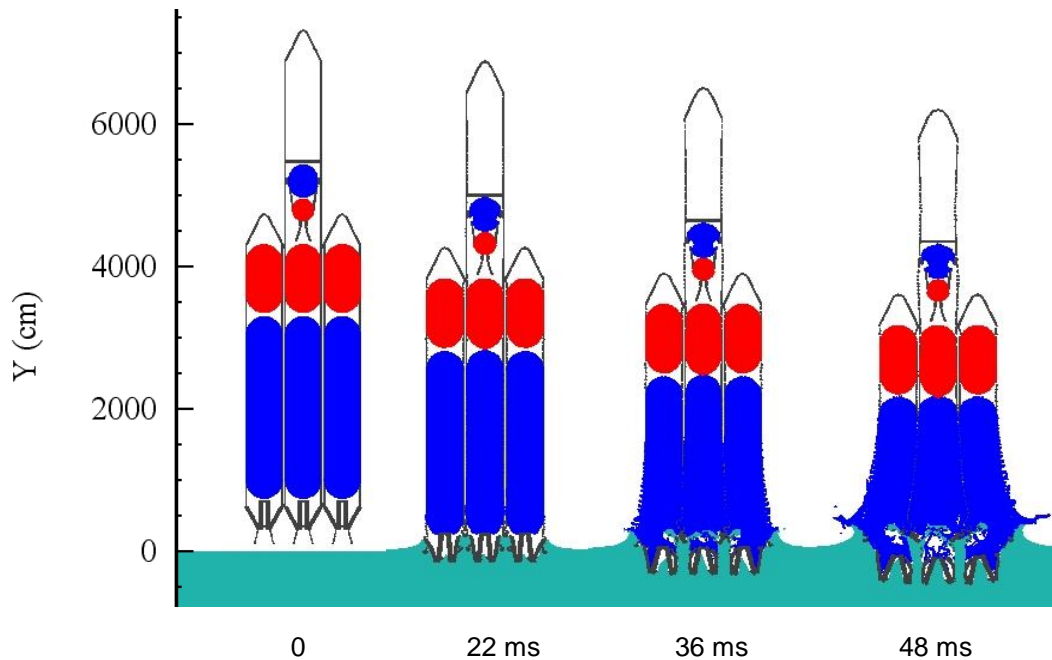

Figure 3. Delta IV Heavy Impact Simulation at 800 fps – Vertical Orientation

Simulation results for Delta IV Heavy vehicle impacting at 90 degrees in the yaw plane (that is, horizontally on edge) at 800 fps onto a granite surface are shown in Figure 4. The images in this figure show a mixing interface appearing in the bulkhead chamber between the propellant components in the bottom (first-impacting) CBC at approximately 12 ms into the simulation. Mixing interfaces appear in the adjacent center and upper CBCs approximately 6 ms and 12 ms later, respectively. Simulation results for the Delta IV Heavy vehicle impacting on edge at a 45-degree angle in the yaw plane at 800 fps onto a granite surface are shown in Figure 5. The images in this figure also show mixing interfaces appearing approximately 6 ms apart in the lower and middle CBCs.
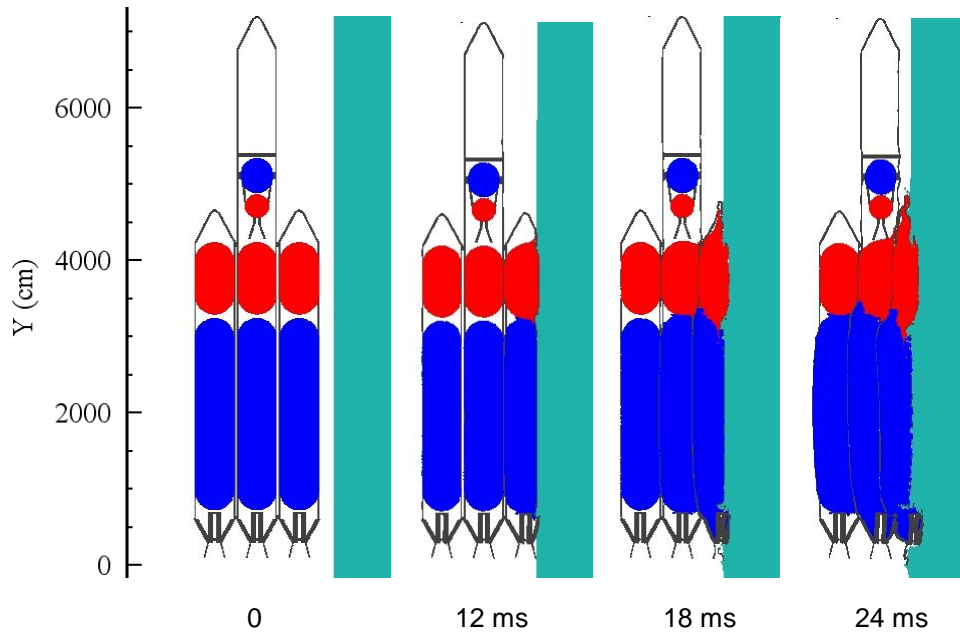
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Figure 4. Delta IV Heavy Impact Simulation at 800 fps – 90 Degree Yaw Orientation
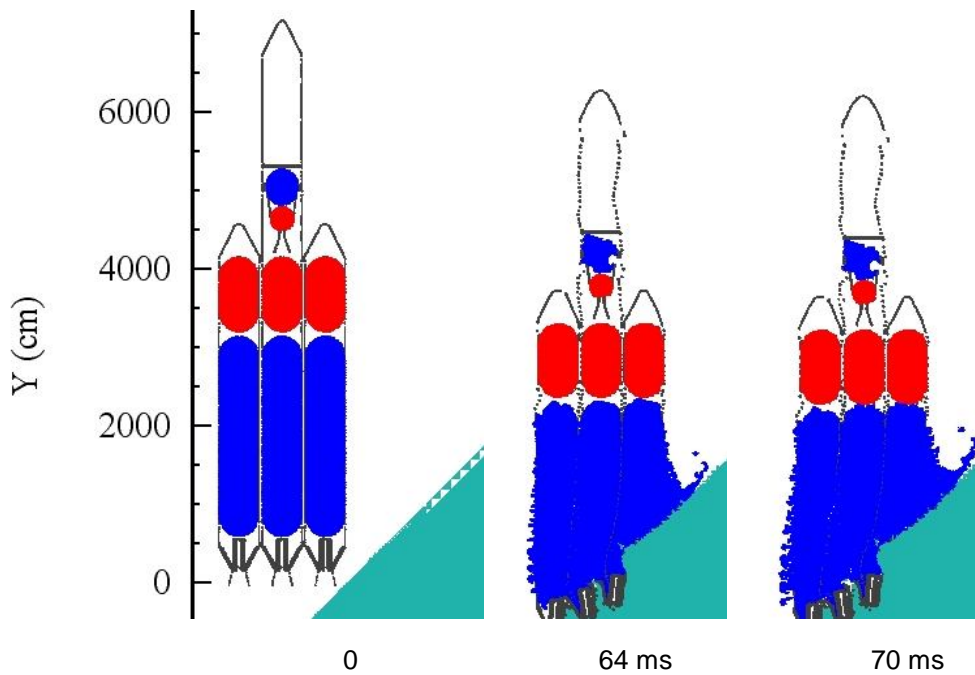

Figure 5. Delta IV Heavy Impact Simulation at 800 fps – 45 Degree Yaw Orientation

For the simulation results shown in the above three figures, estimates of the ignition time delays between the first and second igniting CBCs for the three impact orientations are listed in Table 1. Based solely on the consideration of these estimated ignition time delays, a significant dispersal of the propellants from the CBCs igniting later in the sequence of events reduces the predicted total blast yield. However, further considerations as detailed below suggest that this is not always the case.

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Table 1. Delta IV Heavy Mixing Interface Onset, Time Delay Between in Adjacent CBCs

Vehicle Axis Rotation in Yaw Plane at Impact deg	CBC Ignition Time Delay ms
0 (vertical)	12
45	6
90	6

Further investigations were conducted into the propensity of the expanding combustion products from the first-igniting CBC propellants to disperse the unreacted propellants from adjacent CBCs. To accomplish this, a simulation was performed of the vehicle impacting in the vertical orientation, with energetic materials having the same initial temperature, pressure and density as the cryogenic liquids inserted into the tanks near the mixing interface of the center CBC. The vehicle with energetic materials is illustrated in Figure 6. The relative sizes of the inserted materials closely match the stoichiometric volume ratio of the two propellants. The energy densities were chosen to provide an energy level similar to that contributed by the reacting components. The energy release was programmed to occur over a 1-ms time span beginning at 36 ms into the event, which is the estimated time at which the ignition is predicted to occur, as indicated in Figure 3. The expansion rate from this rapid release of energy roughly matches the initial expansion rate estimated from the HOVI tests discussed above. The programmed energy release is intended to mimic the explosive behavior of the reacting propellants near the interface in the center CBC.
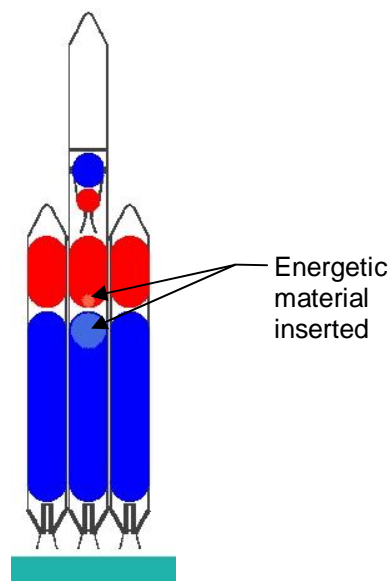

Energetic material inserted

Figure 6. Delta IV Heavy Model with Energetic Material Inserted in Center CBC

The progression of the simulation is shown in Figure 7, with the center CBC propellants colored distinctively to distinguish them from that of the adjacent (non-reacting) CBCs. As seen in this figure, the programmed energy release in the simulation provides an illustration of the inferred driving apart of the outer CBC propellants by the combustion products from the inner CBC. The primary fuel and oxidizer mixing occurs in the center CBC, where the confinement and consequently the explosive pressures are

the greatest. The propellants from the outer CBCs experience only incidental contact where there is little if any confinement, and thus are not expected to contribute substantially to the total blast yield.
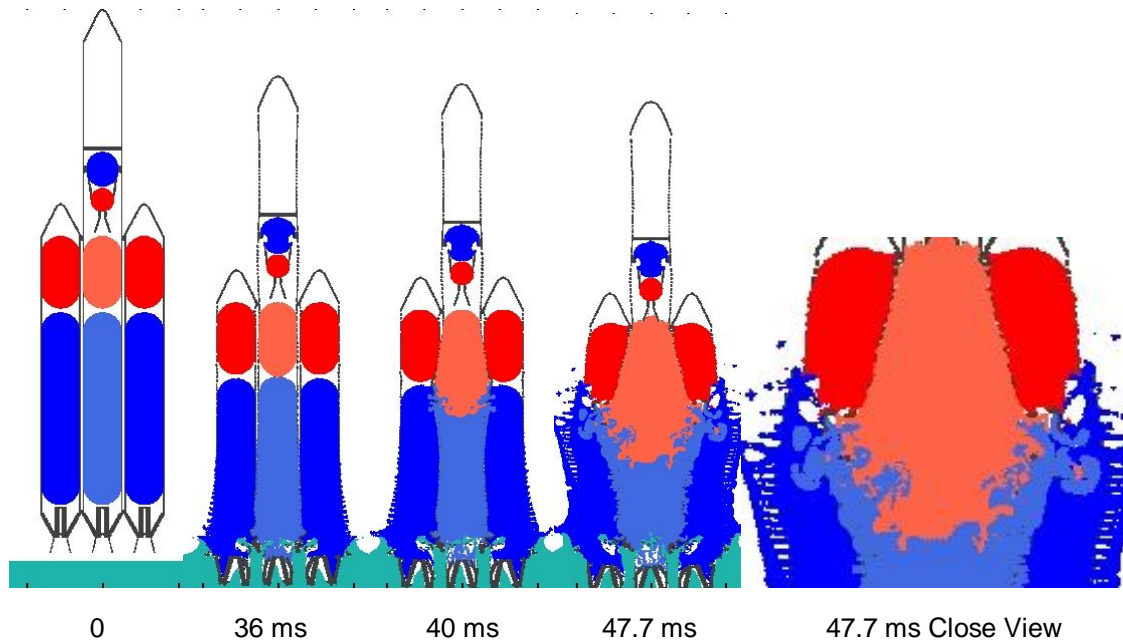

| 0 | 36 ms | 40 ms | 47.7 ms | 47.7 ms Close View |

Figure 7. Delta IV Heavy Vertical Impact Simulation with Inserted Energetic Material Reacting During 36–37 ms Time Range

Although this is not a rigorous simulation of the chemical reactions occurring throughout the system, it does *illustrate* the potential for early reactions in one CBC to disperse unreacted propellants in adjacent CBCs, thereby preventing them from participating in the explosion in the prompt manner necessary to contribute significantly to the total blast yield. To account for this disproportionately low contribution to the yield, a lower limit model of the yield fraction may include the propellant weight from the center CBC and only a tiny fraction (estimated at approximately 1 percent) of the propellants from the adjacent outer CBCs. Since the current study does not account for all of the uncertainties and simplifications discussed above, such a model is not completely validated, but is rather illustrated here. Further simulations with fewer simplifying assumptions are needed to provide a high level of confidence in such a model.

ADVANCED SIMULATIONS

Additional numerical studies were performed to better understand the behavior of the propellant reactions and dispersions during impacts at various angles with the ground. An important example of these later simulations is shown in Figure 8, with the vehicle impacting horizontally on edge, and with energetic material inserted in the lower CBC, causing it to explode upon mixing of its propellant components. In this particular simulation the ground confines the vehicle so as to force the expanding combustion products in the lower CBC to encroach upon the center CBC. Since the density of the LH_2 is less than 10 percent of the LO_2 density, the LH_2 in the lower CBC is readily pushed out of the way by the expanding products. It then moves upward and forces LH_2 in the center CBC to move laterally toward the LO_2 tank dome in the bulkhead. This action causes early mixing of the center CBC propellants, which would lead a secondary explosion in the center CBC, beginning within 4 ms of the primary explosion in the lower CBC.
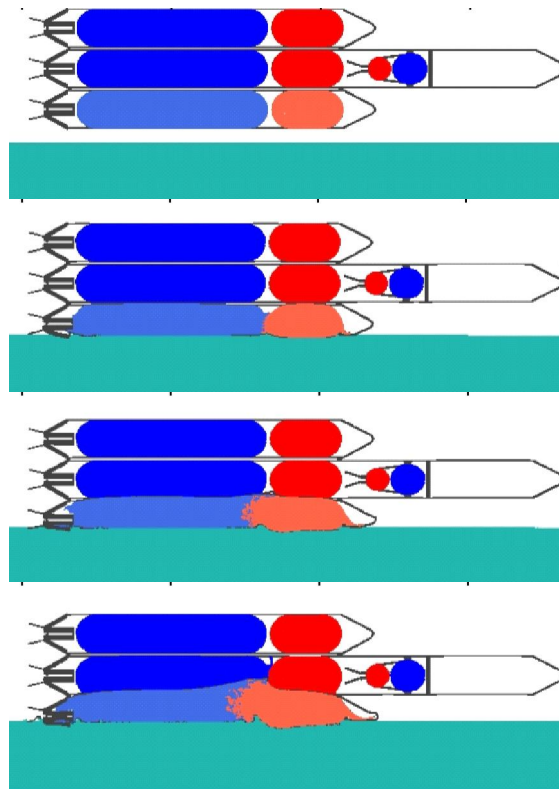
Figure 8. Delta IV Heavy Impact Simulation at 800 fps – 90 Degree Yaw Orientation with Energetic Material Inserted in Lower CBC

Although no energetic material was inserted in the center CBC shown in Figure 8 to simulate the secondary explosion, it is likely that its combustion products would expand into the upper CBC in a manner similar to the expansion of center CBC combustion products for a vertically oriented impact into the adjacent left and right CBCs, as shown in Figure 7. This would result in minimal reactions of the upper CBC propellants during the early phases of the event. Consequently, the horizontal edge-on vehicle impact would appear to most likely result in two of the three CBCs contributing to the overall blast yield.

Similar behavior is seen in impacts that occur at an acute angle with respect to the ground. An example simulation illustrating this phenomenon is shown in Figure 9. In this simulation the vehicle impacts at a 45-degree angle on-edge, as shown in Figure 5, except that the lower CBC has energetic material exploding upon mixing, as in the simulation shown in Figure 7.
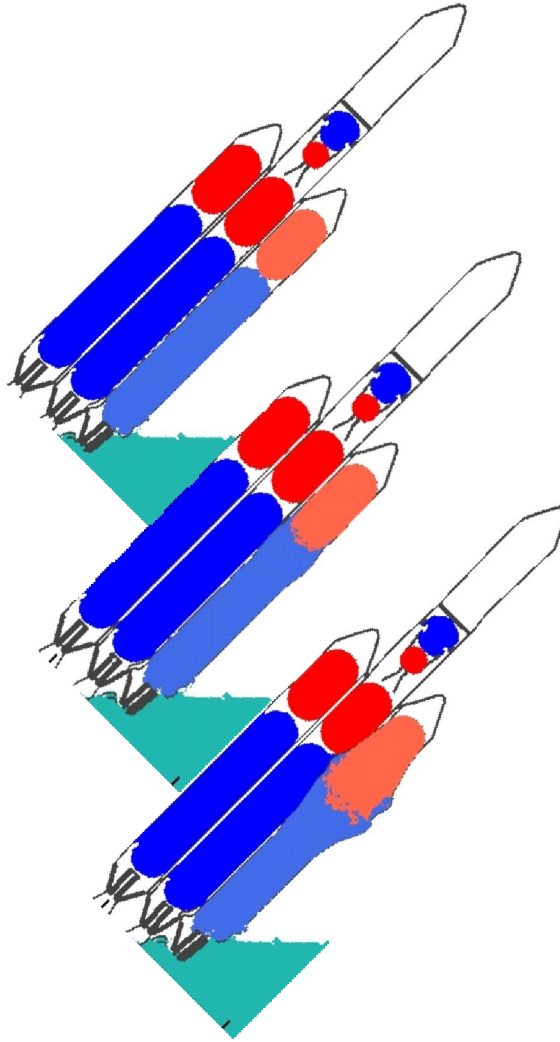
Figure 9. Delta IV Heavy Impact Simulation at 800 fps – 45 Degree Yaw Orientation with Energetic Material Inserted in Lower CBC

Although the lower CBC explosion shown in Figure 9 occurs well above the ground, and so is not enhanced by any possible confinement from the ground surface, the center CBC is nevertheless impinged upon by the lower CBC expanding combustion products. Since the upper CBC is abutted to the center CBC, it acts as an inertial backstop that delays the propellant expansion, allowing the LH_2 to permeate the center bulkhead region. This results in early mixing of the propellants in the center CBC and a significant contribution of its combustion products to the early blast wave-producing phases of the event. Since the upper CBC is less confined than the center CBC, it would be unlikely to participate in such a manner as to contribute significantly to the overall blast yield, just as the upper CBC in the horizontal impact shown in Figure 8 would be unlikely to participate in the early phases of the event.

Although the vertical impact simulation shown in Figure 7 suggests that only one CBC would contribute significantly to the overall blast yield, this is a special case with a highly symmetric distribution of materials about the axis of motion, leading to the center CBC exploding first. In general the vehicle will not impact with perfect symmetry, and it is more likely that one of the outer CBCs closest to the ground will react first. Thus a relatively safe assumption is that two of the three CBCs will participate as a general rule for most edge impacts, the exceptions being for the rare cases where the impact is highly symmetric

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with the vehicle either upright or in a horizontally pitched orientation (as opposed to the horizontal orientation about the yaw axis shown in Figure 8).

The general prediction, then, based on the 2D simulations with programmed explosions is that two out of three CBCs will generally contribute to the blast yield. While the initial impact simulations the vehicle impacting vertically suggest that only one CBC contributes to the blast, more generalized impact simulations do not support that conclusion. However, the 2D simulations, by virtue of the geometry they use in representing the vehicle, tend to overestimate the inertial confinement of the expanding combustion products relative to that for an actual vehicle existing in a 3D space, such that a single CBC participating in the blast may actually provide a more accurate representation of the actual event.

For this reason, an attempt was made to set up and perform a 3D simulation. The model for the simulation is shown in Figure 10, with propellants, tanks, internal hardware, and exterior shells shown in a layered construction. Unfortunately, the 3D model is too computationally intensive to run on a PC, and may even be too large to run on a multi-node system with ten times the power of a PC. A sizeable cluster exceeding the currently available resources is needed to support simulations of this type.
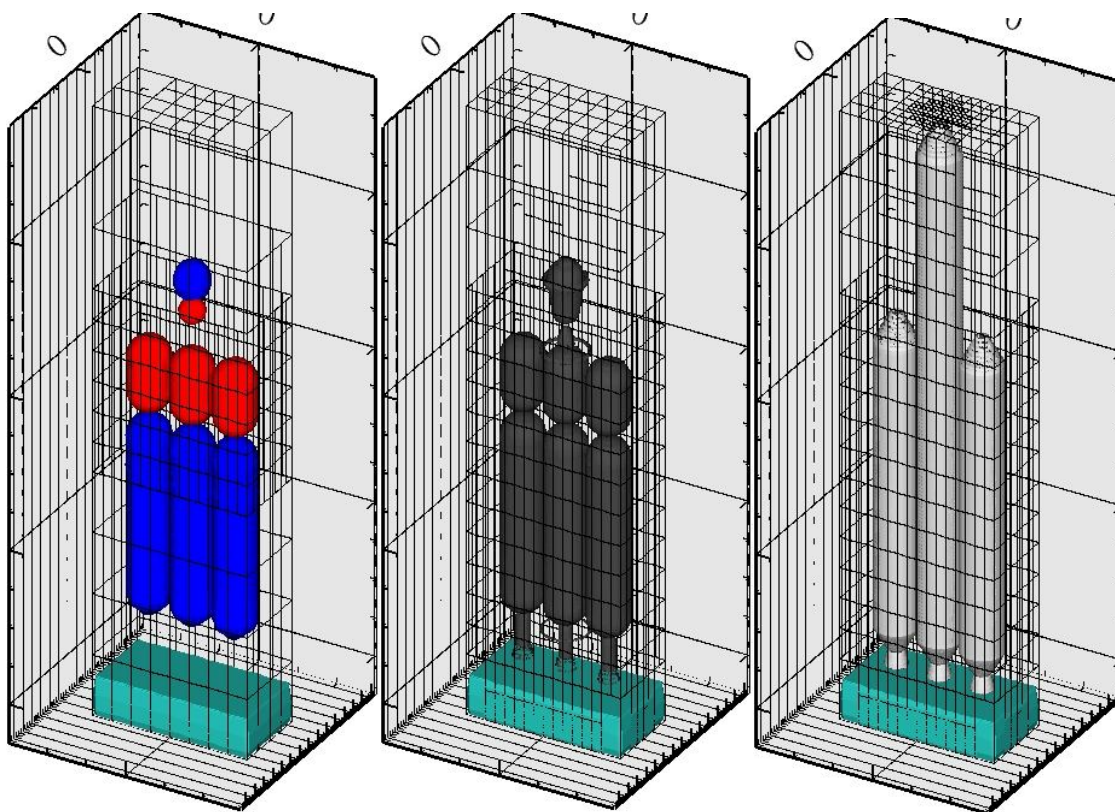

Figure 10. Delta IV Heavy Impact Simulation Model with Propellants, Hardware and Exterior

CONCLUSIONS

Initial investigations showed that there is a potential for a blast yield to occur that involves little or no participation of the propellants in two of the three CBCs, and that only one CBC is certain to participate significantly. However, further numerical studies revealed that the center CBC will likely be involved along with one of the outer CBCs impacting before the others. The opposite outer CBC, which is furthest from the ground, is subjected to relatively little confinement, and is thus less likely to participate in the

blast. This leads to the conclusion that a good interim estimate of the yield histogram is based on two of the CBCs (along with the second stage propellants) participating in the blast. The remaining CBC is then assumed to contribute a maximum of only one percent of its propellant weight to the blast. Propellant weights derived from these quantities are used along with the PYRO yield curves for hard surface impacts to provide two separate yield models for the Delta IV Heavy vehicle impacting intact.

This conclusion is based on the results of 2D hydrocode simulations, which may overestimate the effects of confinement on the prompt mixing of the propellants. 3D analyses would better characterize the propellant confinement and dispersal, possibly supporting the use of the low-yield model (with the participation of only one CBC) in the development of the yield histogram.

The high-yield model and the low-yield model provide approximate upper and lower limits, respectively, to estimates of the yield ranges that may potentially occur during an actual vehicle impact. The intermediate 2-CBC yield model provides an interim estimate of the possible yield ranges. Further studies may provide a basis for assigning a relative uncertainty to each of these models, or replacing them altogether with a model that better captures the 3D spatial characteristics of the impact event.

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Sponsored by 30th Space Wing, Vandenberg AFB

Liquid Propellant Explosion: German V-2 Rocket
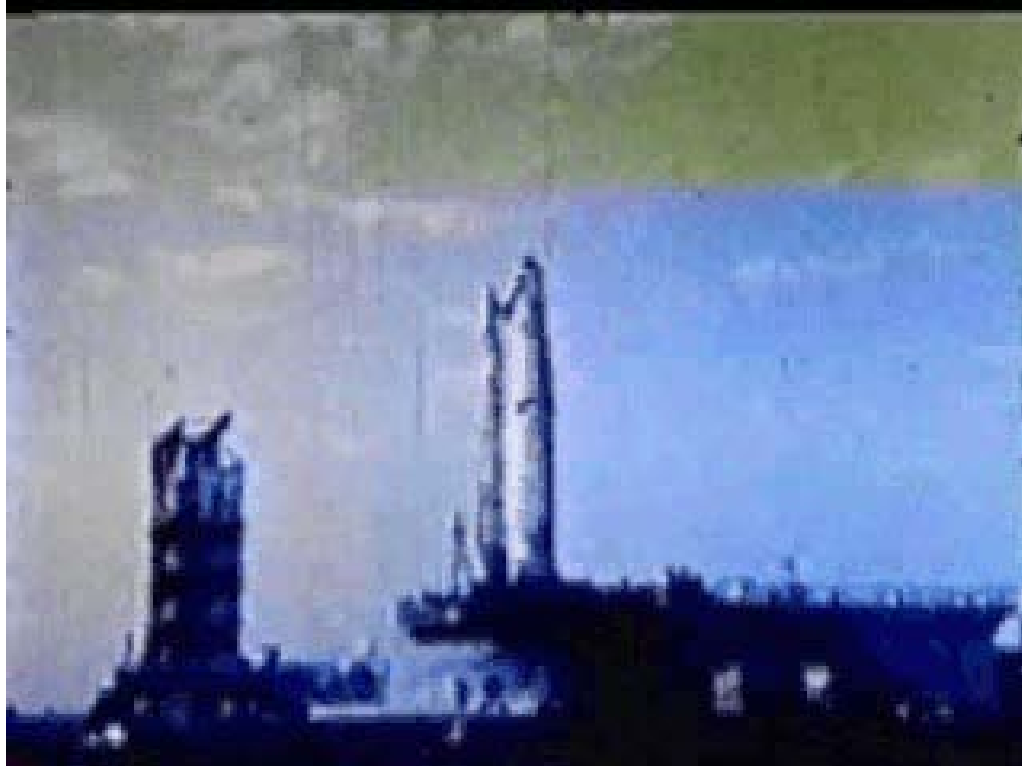

Liquid propellant explosions create fire balls and some air blast
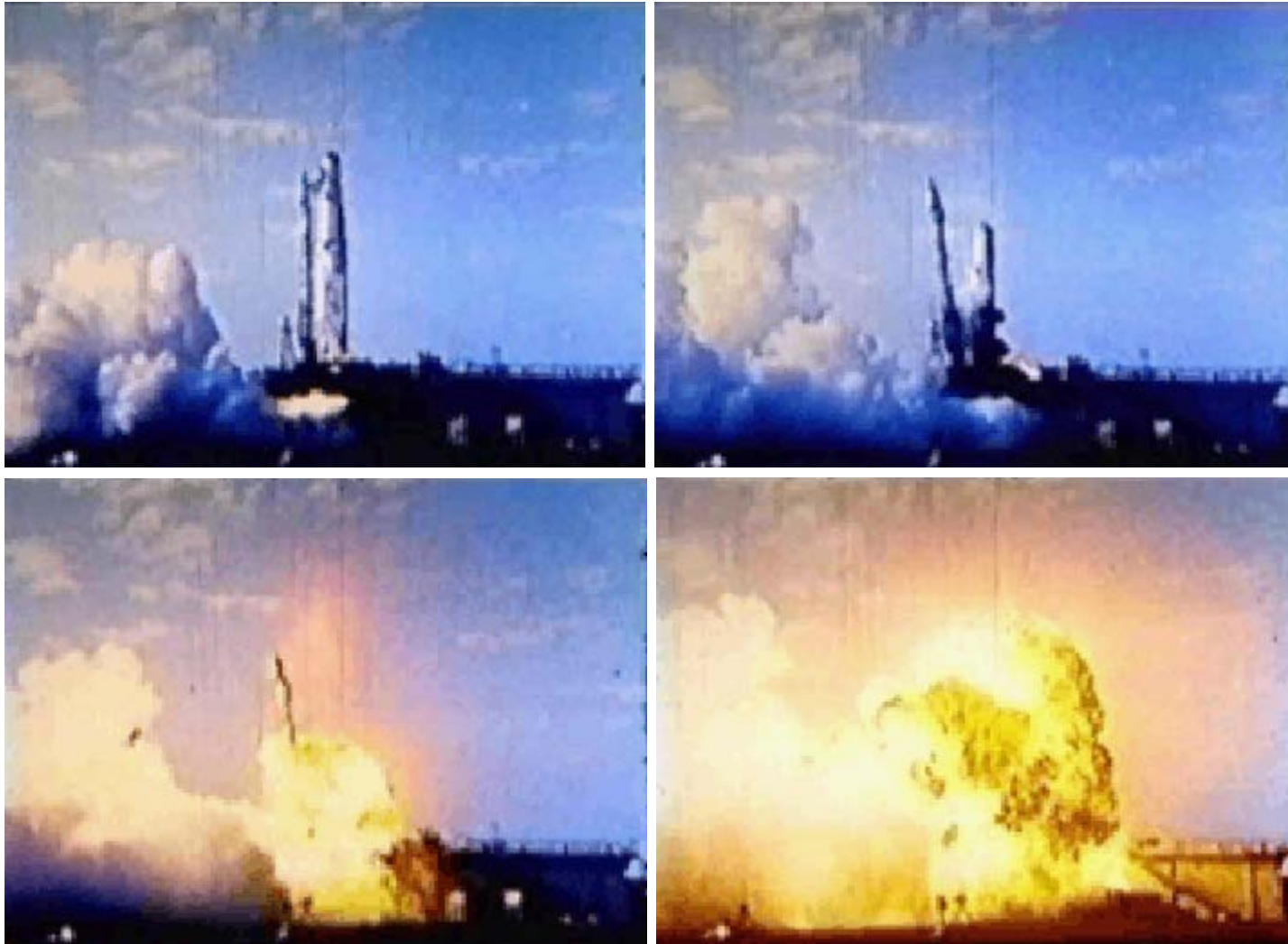
Liquid Propellant Explosion: Titan I

Liquid propellant explosions create fire balls and some air blast

Liquid Propellant Explosion: Atlas D

Liquid propellant explosions create fire balls and some air blast

ACTA

Atlas D Low Speed Vertical Impact On Pad

Liquid propellant explosions create fire balls and some air blast

ACTA

Delta IV Heavy Vehicle

- The Delta IV Heavy vehicle can place up to 13 tonnes of satellite payload into GS orbit
  - 23 tonnes into LE orbit
- It has 3 Common Booster Cores (CBCs)
- Each CBC contains a maximum of approximately 450,000 lb of liquid oxygen (LO2) and liquid hydrogen (LH2)
  - Ratio LO2:LH2 = 5.8:1
- The second stage contains 60,000 lb LO2/LH2
  - Much smaller than Stage 1
- An on-pad explosion would involve up to 1.41 Mlb of propellants
- The participation of all 3 CBCs in supporting the initial blast wave is being investigated

ACTA

Current Liquid Propellant Yield Models
for Impacts of Intact Vehicles

Typical liquid propellant vehicle

Liquid Propellants
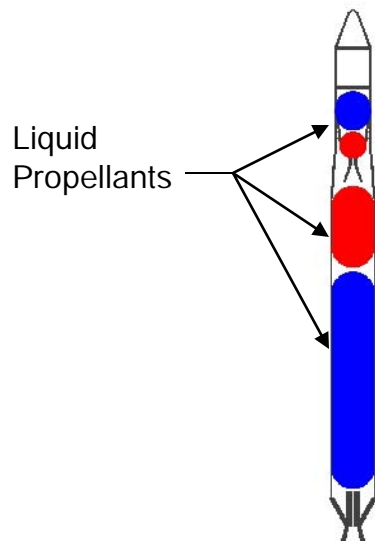
Yield Models for Intact Impacts
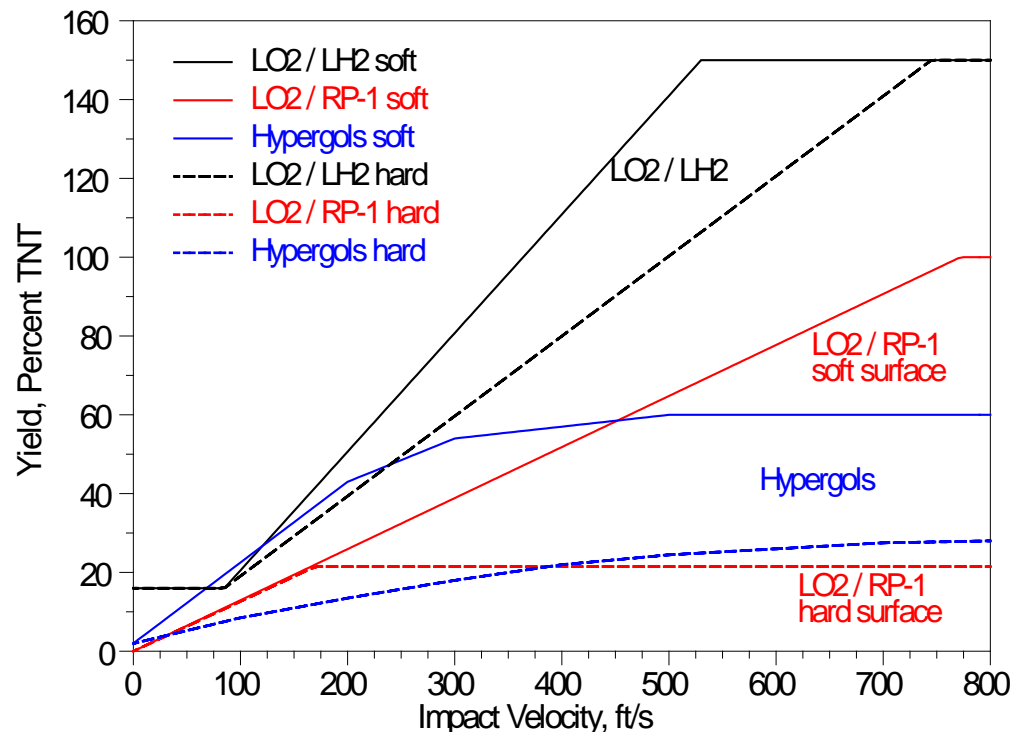
Blast yields vary with propellant type, weight, impact speed and impact surface hardness

# Delta IV Heavy Combined Yield Histograms
for Western Range Launches
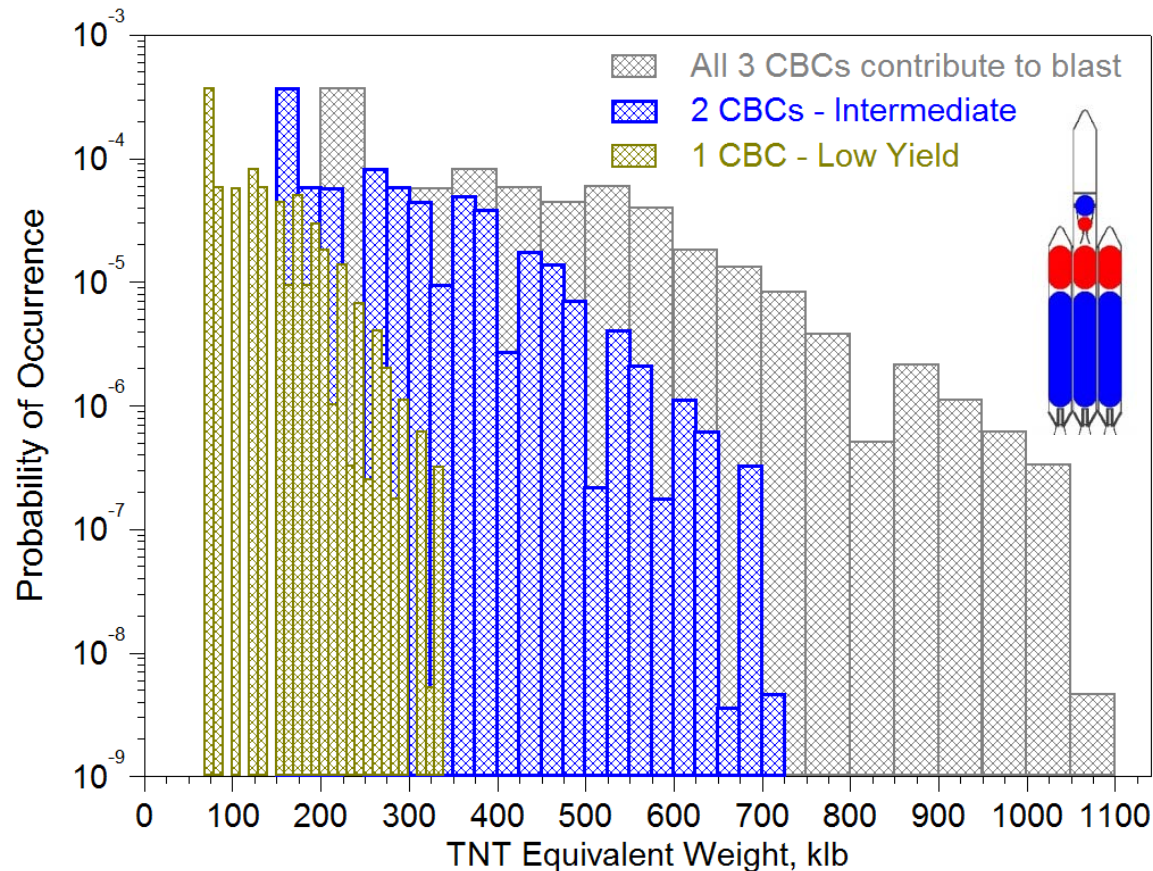
The number of CBCs contributing to the blast wave greatly affects the potential yields

Previous Analysis: Delta IV Medium Upright Vertical Fallback at 800 fps into Dry Sand
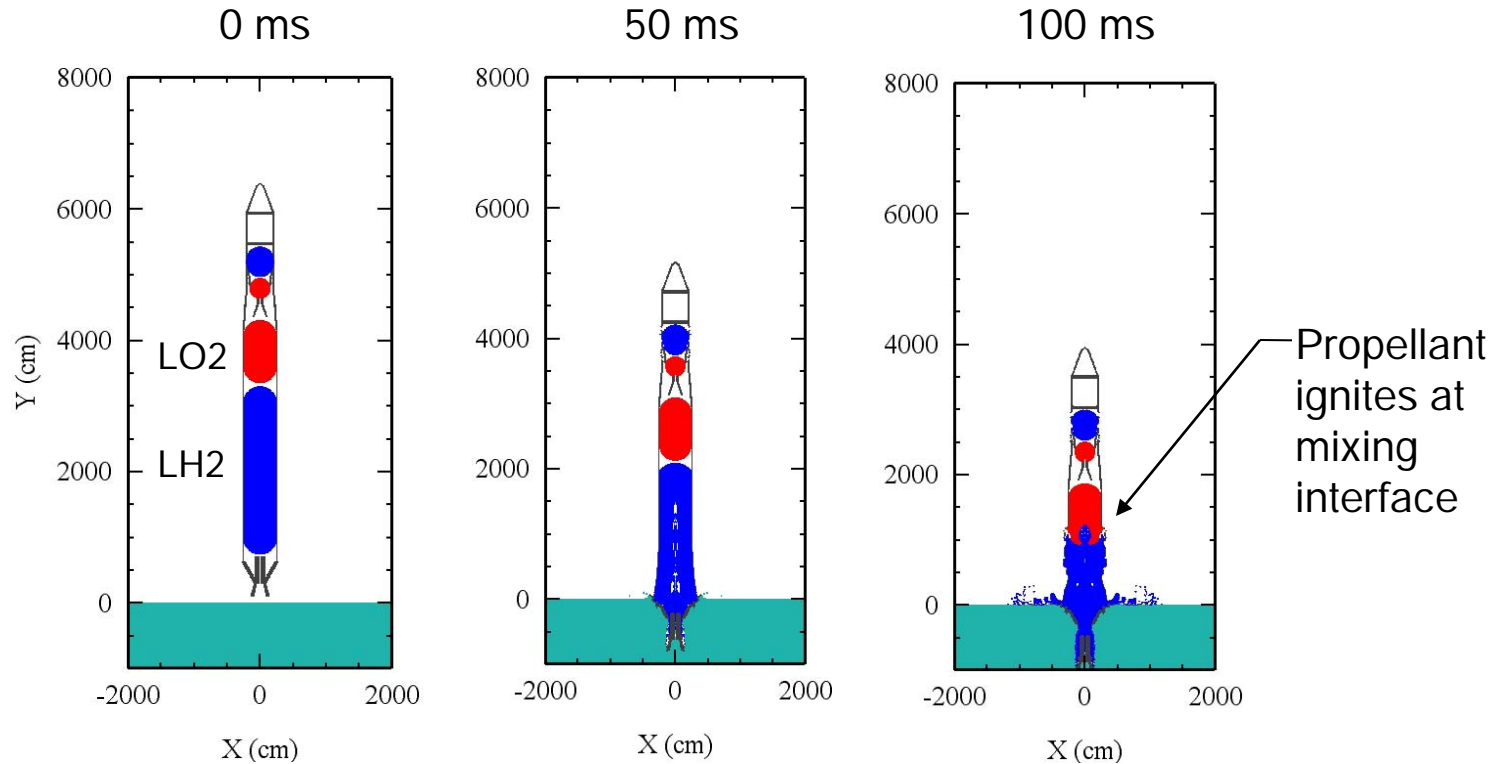
Ignition of propellants is expected at an elevation well above the ground surface
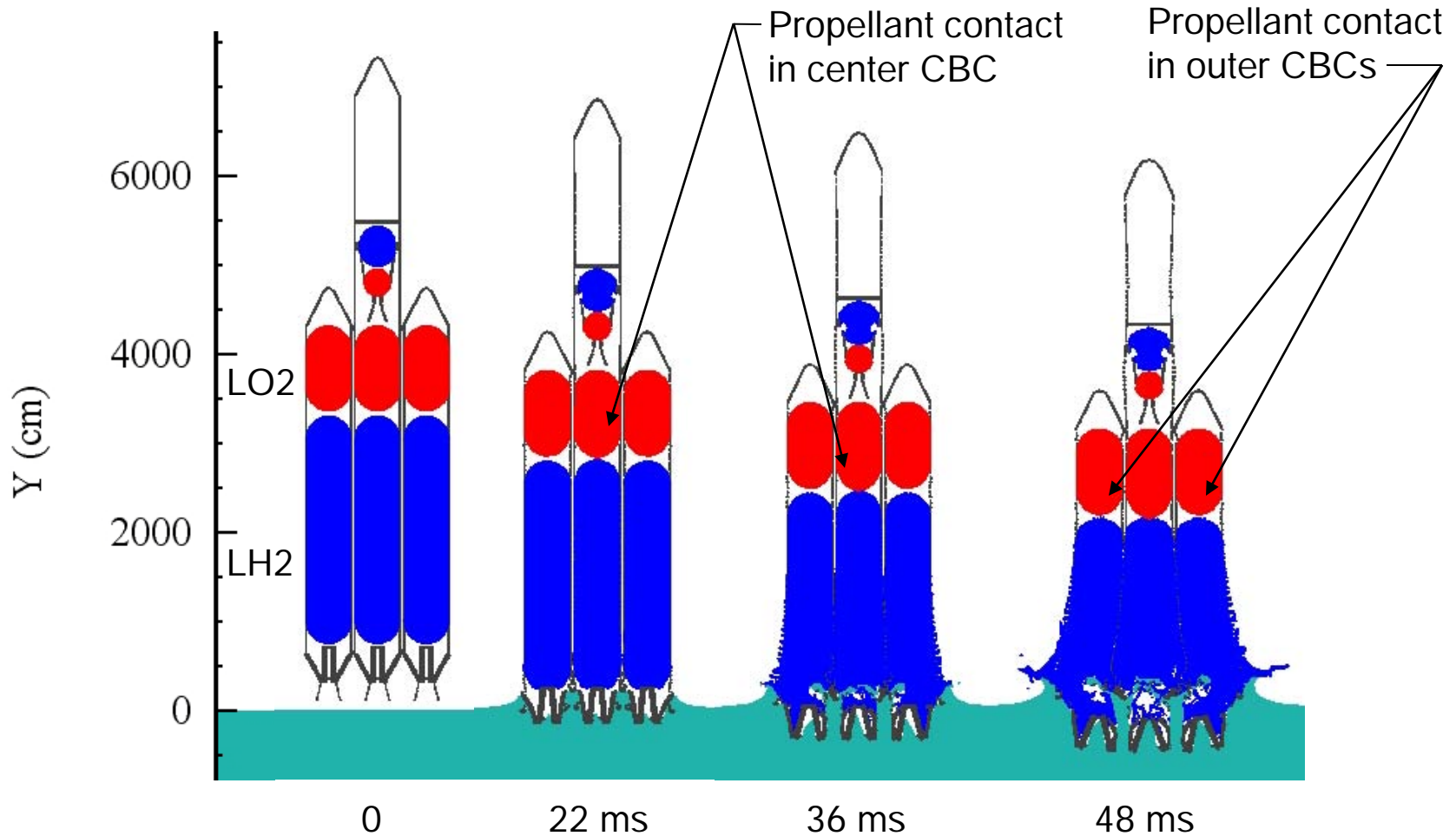
Previous Analysis continued: Stresses in Delta IV Medium for Upright Fallback at 800 fps into Dry Sand
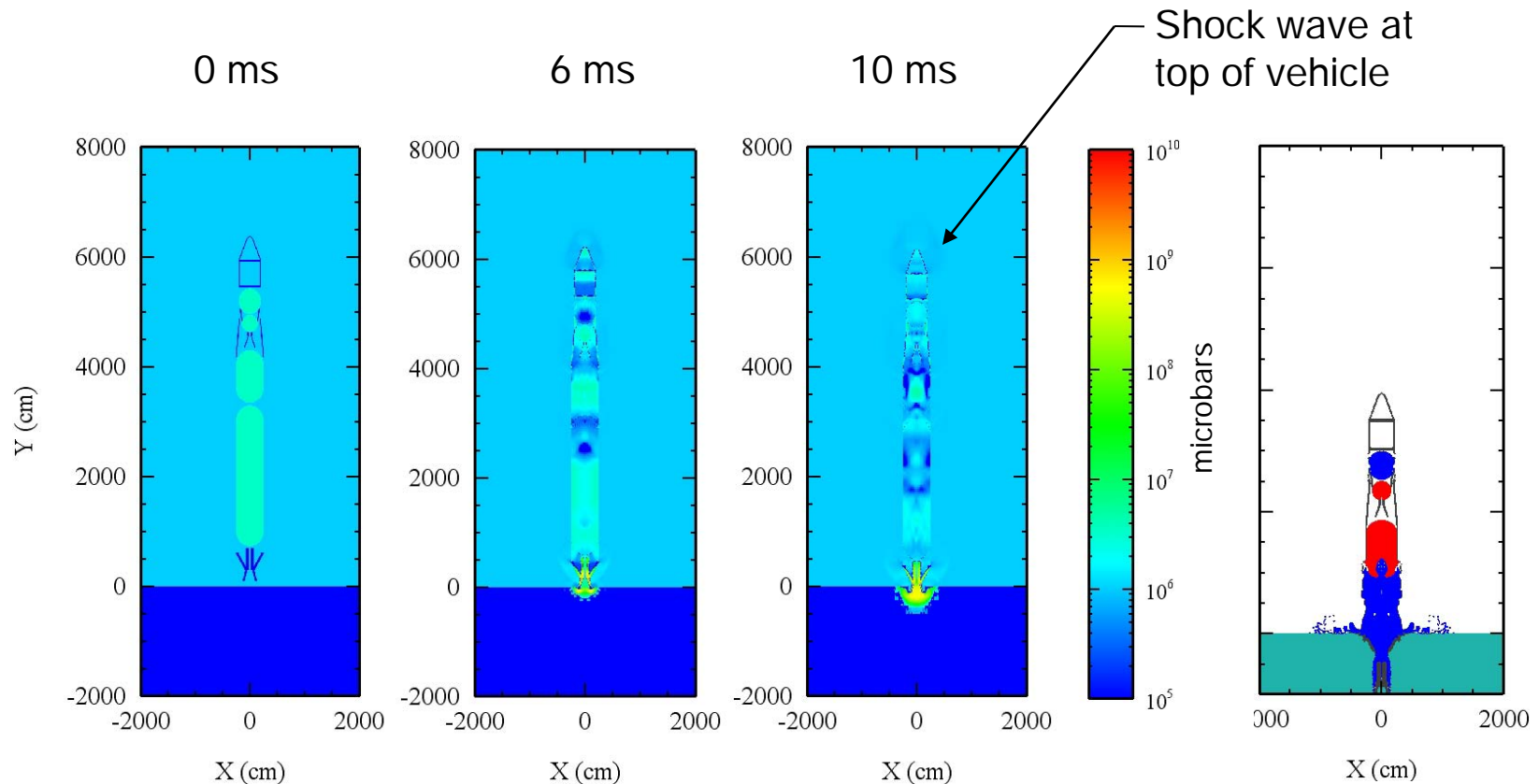
Shock wave travels much faster through the vehicle than the vehicle travels downward
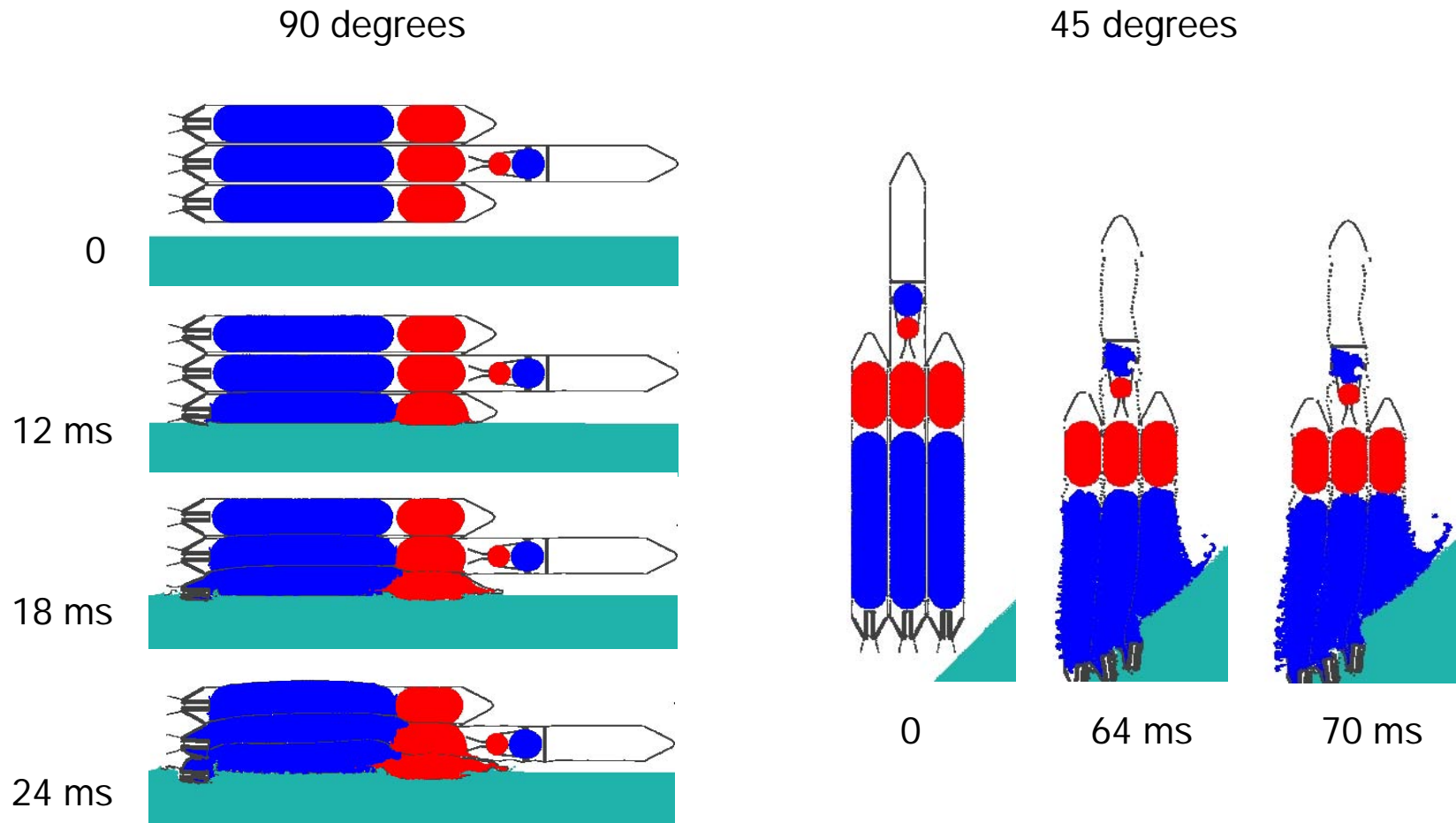
Delta IV Heavy Impact Simulation
Upright Fallbacks at 800 fps

Propellant contact in center CBC

Propellant contact in outer CBCs

Y (cm)

6000

4000 — LO2

2000 — LH2

0

| 0 | 22 ms | 36 ms | 48 ms |

Propellants in center CBC begin to mix prior to those in outer CBCs
Delay time between breaching CBCs is at least 12 ms
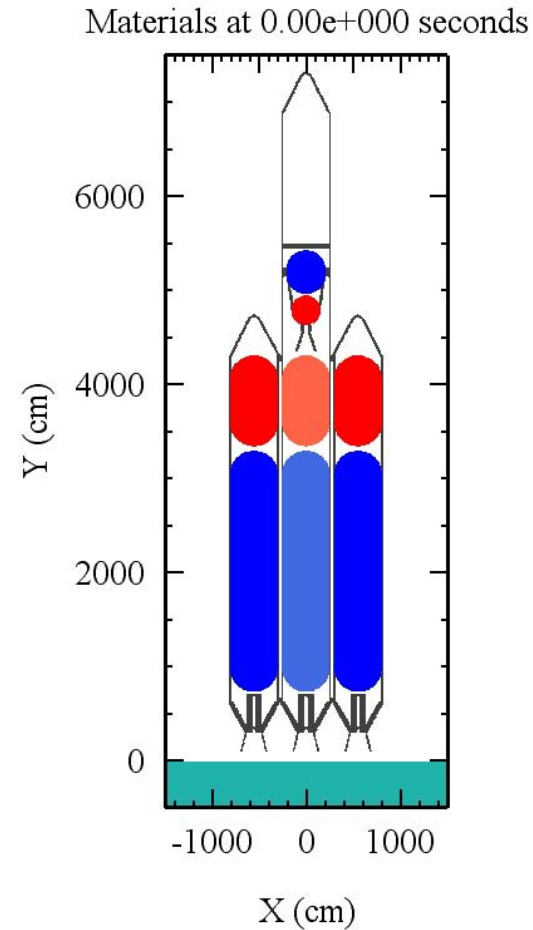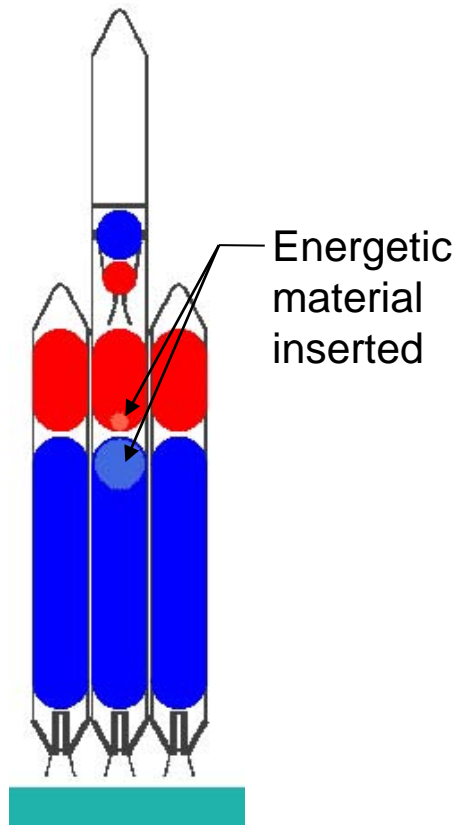
ACTA

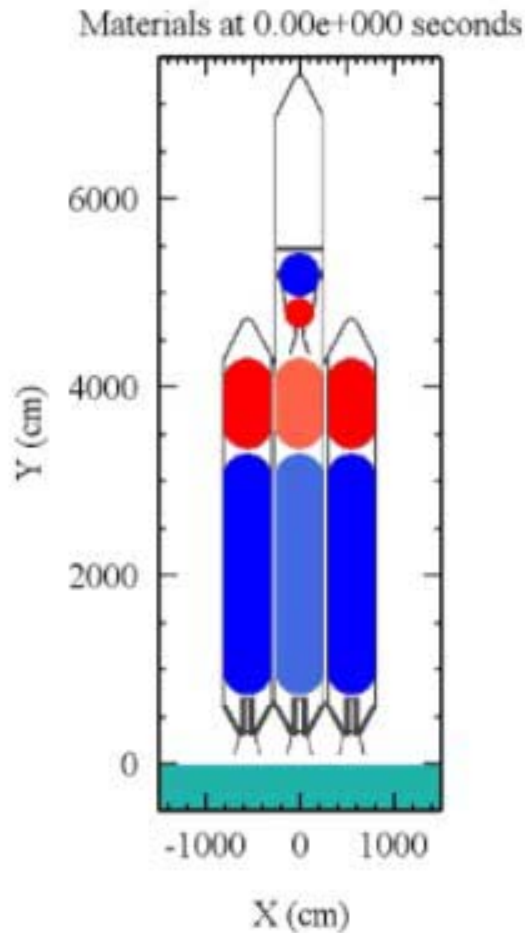# Delta IV Heavy Impact Simulation
90 and 45 degree Yaw Fallbacks at 800 fps

90 degrees

45 degrees

0

12 ms

18 ms

24 ms

0   64 ms   70 ms

Delay time between breaching CBCs is approximately 6 ms

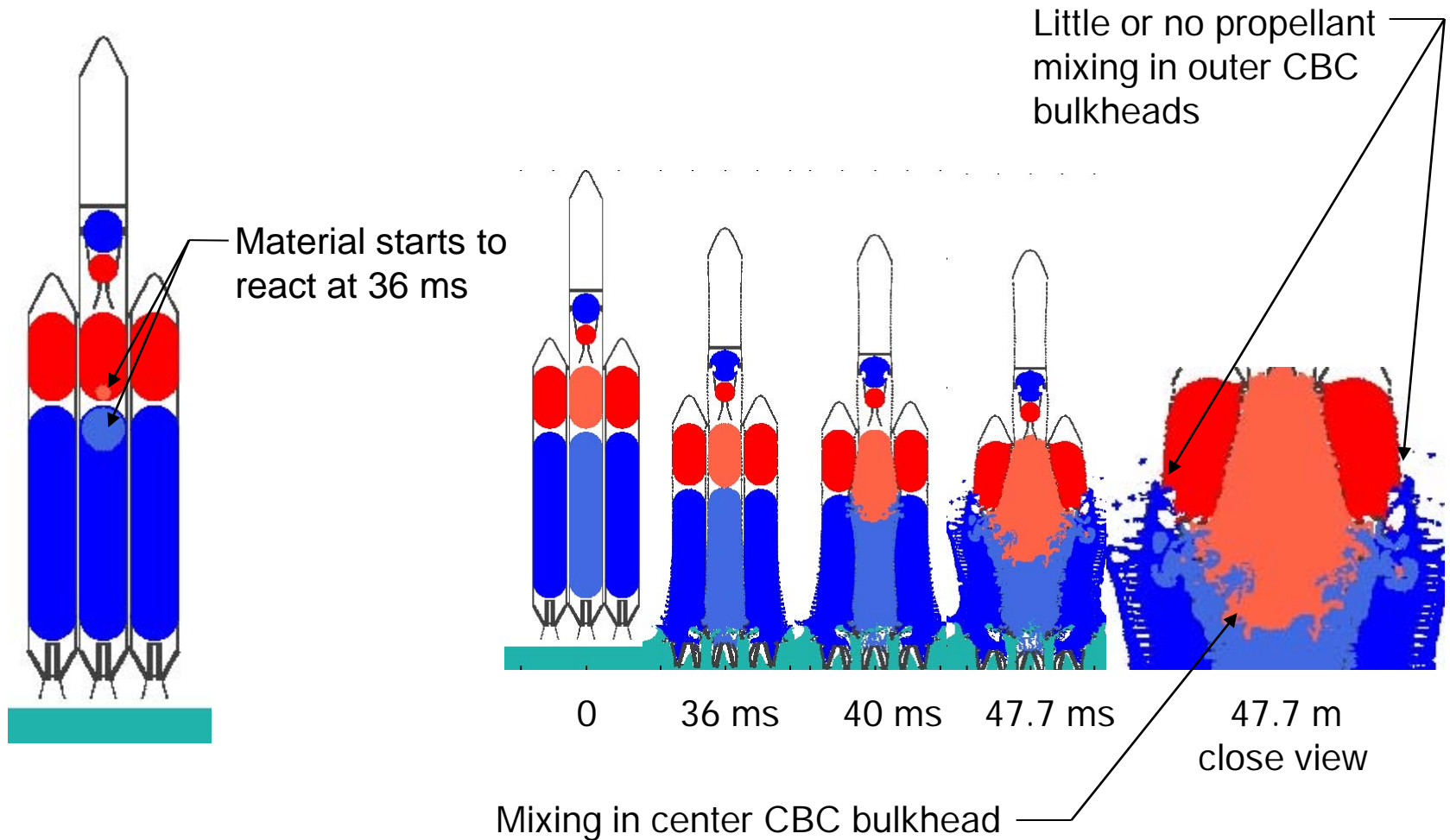# Delta IV Heavy Impact and Explosion Vertical Fallbacks at 800 fps

Energetic material inserted

Materials at 0.00e+000 seconds

Delta IV Heavy Impact and Explosion
Vertical Fallbacks at 800 fps

Materials at 0.00e+000 seconds

Delta IV Heavy Impact and Explosion
Vertical Fallbacks at 800 fps

Little or no propellant mixing in outer CBC bulkheads

Material starts to react at 36 ms

0   36 ms   40 ms   47.7 ms   47.7 m close view

Mixing in center CBC bulkhead

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Delta IV Heavy Impact and Explosion
90 and 45 degree Yaw Fallbacks at 800 fps

90 degrees

45 degrees

Combustion pushes low density
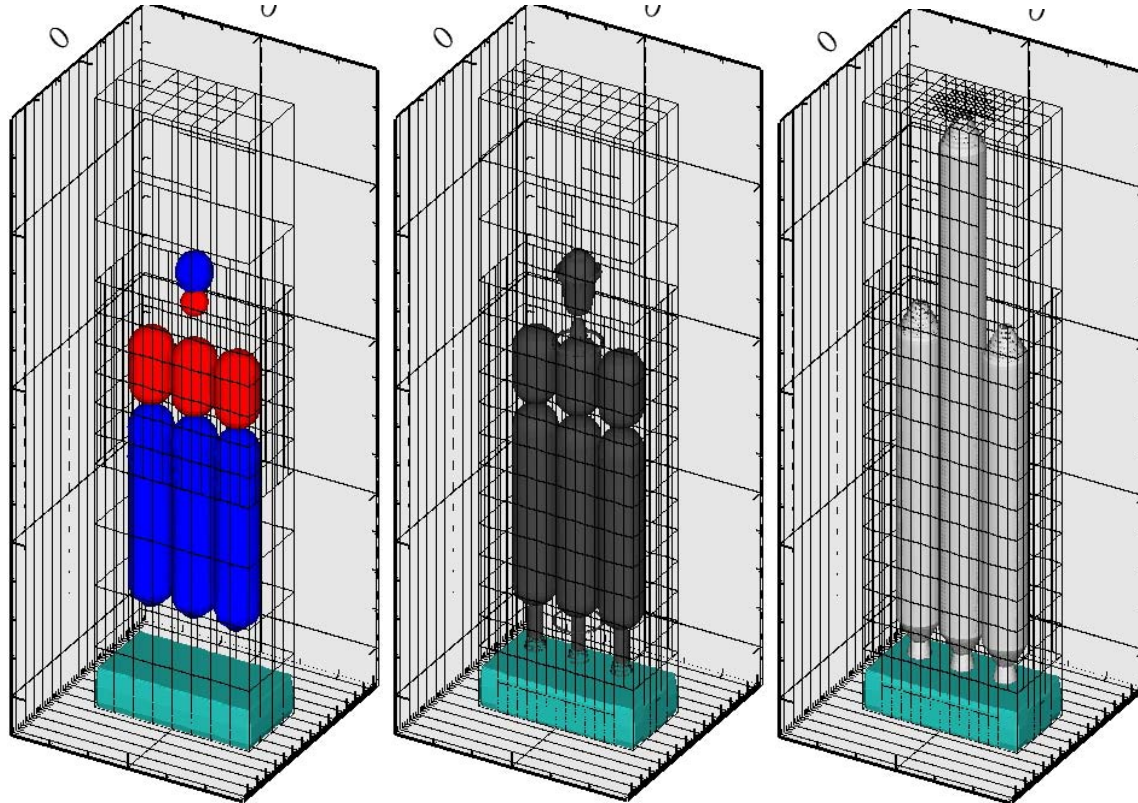LH2 upward into adjacent tank
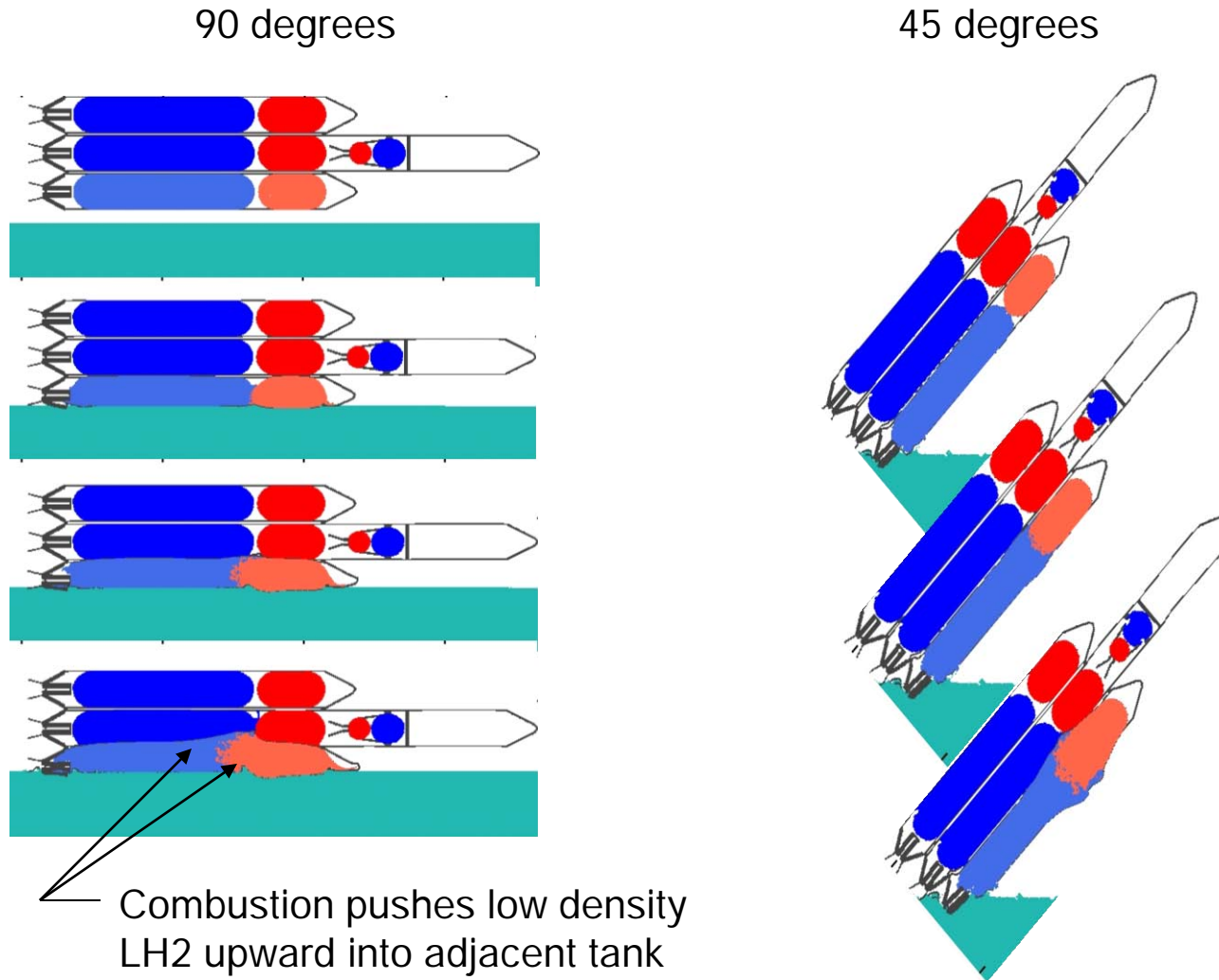
Propellant mixing occurs early in both lower and center CBC bulkheads

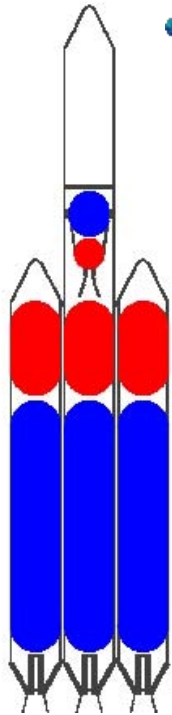# Delta IV Heavy 3D Impact Simulation Model

Propellants   Hardware and Tanks   Exterior

Multi-layer 3D model will require large cluster to perform calculation

Conclusions for Liquid Propellant Yield Models

- Only one of the CBCs is certain to participate in the blast wave generation
    - One or two CBCs will most likely separate with little propellant mixing
- A good interim estimate of the yield histogram is based on two of the CBCs participating in the blast
    - The second stage is included
    - In all cases the center CBC will likely be involved along with one of the outer CBCs impacting before the others
    - The opposite outer CBC, furthest from the ground, sees little confinement, and is thus less likely to participate in the blast

- This conclusion is based on 2D hydrocode simulations, which may overestimate the confinement of the promptly mixing propellants
- A 3D model was developed to better capture the spatial characteristics
    - Use of this model is computationally expensive and awaits funding